Fluxes of Inorganic Nitrogen between Sediments and Water in a Coral Reef Lagoon

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Lagoon sediments of coral reefs are potentially important sites of nutrient regeneration. Profiles of ammonium within sediments at One Tree Island, southern Great Barrier Reef, showed strong gradients with values as high as 50μg atoms NH_4^+-N.l^{-1} at 15cm depth decreasing to around 8μg atoms.l^{-1} just below the surface. Gradients of NO_3^-/NO_2^- also existed but concentrations were much lower than for ammonium, ranging from undetectable levels to approx. 8μg atoms.l^{-1}. Overlying waters characteristically have low to undetectable levels of dissolved ammonium or nitrate/nitrite. Nutrient profiles were examined in the top 0-10cm of two sediment types and despite strong concentration gradients, no efflux of NH_4^+ ions or NO_3^-/NO_2^- ions were observed from the sediment into the water column. In experiments where the water under domes was artificially enriched with ammonium chloride to maximum sediment concentrations (50μg atoms NH_4^+-N.l^{-1}) rapid uptake of NH_4^+-N by sediments was shown to occur. Microbial processes such as nitrification, denitrification, and ammonium utilization by psammolithic algae in the uppermost layers of sediment may be responsible for the observed phenomena.

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INTRODUCTION

Since the pioneering work of Odum and Odum (1955), Wiebe *et al.* (1975), and Webb *et al.* (1975), different aspects of nitrogen dynamics on coral reef ecosystems have been investigated (e.g. Wiebe, 1976; Smith and Jokiel, 1975; Webb and Wiebe, 1975; Capone *et al.*, 1975; Hatcher and Hatcher, 1981; and Koop and Larkum, 1987). Apart from the work of Entsch *et al.* (1983) and Williams *et al.* (1985), however, there are few published studies on nitrogen cycling in coral reef sediments, although many such studies exist for other environments (see e.g. Raine and Patching, 1980; Hopkinson and Wetzel, 1982).

Nitrogen fixation is widely believed to be responsible for supplying large amounts of nitrogen to coral reef ecosystems (Webb *et al.*, 1975; Wilkinson *et al.*, 1984; and others) although Koop and Larkum (1988) have shown that only 10-15% of nitrogen requirements of primary producers at One Tree Island, southern Great Barrier Reef, can be met by direct nitrogen fixation. There is still a substantial deficit which must be met from other sources such as remineralization by microorganisms.

This study assesses the role of sediments as a source of recycled nitrogen for the adjacent systems by measuring levels of ammonium, nitrate and nitrite within sediments as well as fluxes of these ions between sediments and the overlying water column in One Tree Is. lagoon, southern Great Barrier Reef.

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Materials and Methods

Sites

The whole of this work was conducted in the main lagoon on One Tree Island Reef, Great Barrier Reef, Australia (lat. 20°30′S, long. 152°06′E), (Fig. 1) during summer, 1984.

Nutrient fluxes were measured in the two sediment types representing the range in sediment environments found in One Tree Is. lagoon. These were very fine sand and coarse sand with >40% of particles <63μm diameter and >40% of particles >1mm diameter respectively.

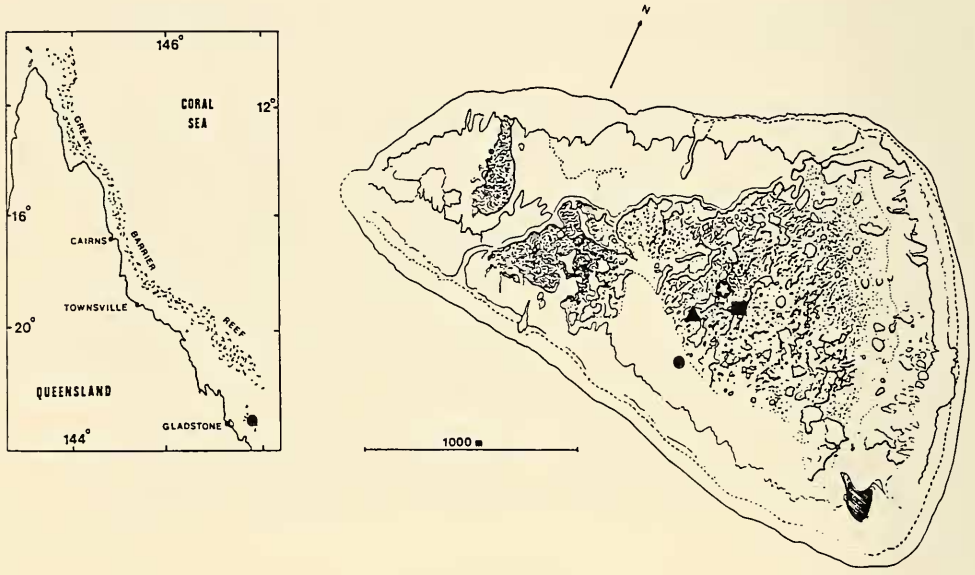

Fig. 1. One Tree Island reef, southern Great Barrier Reef showing (**B**, right) experimental sites in two sediment types.

• Coarse sand; * Very fine sand.

Mean water depth was 4.5m at the site with very fine sand and 1.5m at the site with coarse sand. All sediments in One Tree lagoon contain approx. 97% calcium carbonate, derived from the fringing and patch reefs.

Pore Water Sampling and Analysis

Four replicate cores 5cm diameter and 20cm deep, were taken randomly in areas of each sediment type and subsamples of $10cm^3$ were taken at depths of 0.5, 2.5, 5.0, 10.0 and 15.0cm from each core. The pore water from each subsample was extracted by centrifugation at 3,000 × g for 10 minutes and the concentration of ammonium, nitrate and nitrite ions determined according to Strickland and Parsons (1972). All analyses were conducted within 2 hours of core collection. Nitrate and nitrite analysis was conducted using a Technicon auto-analyser, model AA1.

Rates of efflux of NH_4^+ from the sediments were calculated using the equations of Rutgers van der Loeff *et al.*, (1984):

$$J = \phi D_s . dC/dx \quad (Equation\ 1)$$

where J = rate of flux,
ϕ = sediment porosity,
D_s = effective diffusion coefficient,
dC/dx = concentration gradient across the sediment/water interface.

Measurement of Sediment Fluxes

Measurement of fluxes of ions from the sediment were carried out using six polycarbonate domes placed randomly over the sediment at each site. The domes had a volume of 36 litres with a basal area of 640cm^2 and were anchored to a steel skirt pushed 5cm into the sediment. The skirt also served to prevent lateral movement of water under the edge of the domes.

In each dome, water above the sediment was sampled every 2 hours for 18 hours, using a 20ml syringe and needle pushed through a self-sealing sampling port on the side of the dome. An equal amount of seawater was allowed to enter the dome during sampling to prevent water being drawn from the sediment itself.

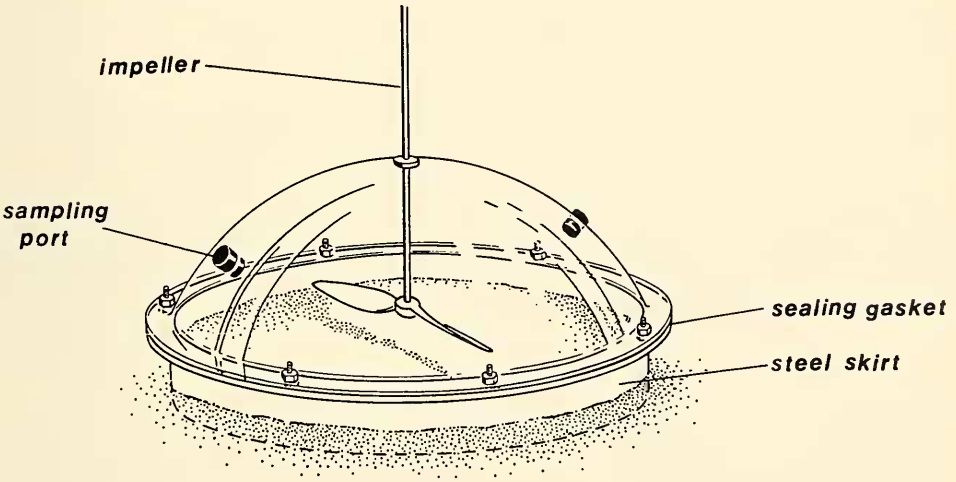

Fig. 2. Dome enclosures used for flux measurements and enrichment experiments showing hand driven impeller, sampling ports and anchoring base.

The water inside each dome was stirred with a hand-driven impeller mounted in its centre (Fig. 2) for 5 minutes every hour, and just prior to sampling. Care was taken to ensure that the stirring rate was low enough to leave the sediment undisturbed, but strong enough to ensure thorough mixing of the dome water.

Samples were immediately refrigerated for transport to the laboratory and analysis for ammonium, nitrate and nitrite ions was carried out within 5 hours of collection as for pore-water samples.

Enrichment Experiments

In experiments using four replicate domes placed randomly over the sediment at each site, the water under the domes was enriched with ammonium chloride to produce a concentration of dissolved ammonium ions approximately equal to the maximum concentration found in the underlying sediment. Four control domes were also set up at

each site with no enrichment. Water in all domes and their immediate surrounds was sampled every 2 hours for 17 hours and the samples analysed for ammonium concentration, oxygen concentration, pH, and temperature.

Also, as a control for uptake of ammonium by organisms in the water column, twelve 500ml bottles, 6 light-proof and 6 transparent, were filled with seawater taken at each site and enriched with ammonium chloride to the same concentration as the enriched domes. Controls were incubated *in situ* for the duration of the enrichment experiment and sampled at the start, midway, and at the end of the experiment. The samples were analysed for dissolved ammonium as before.

Temperature and dissolved oxygen were measured *in situ* with a submersible combination temperature/oxygen probe attached to a YSI meter (model number 57; Yellow Springs Instruments, Ohio, U.S.A.). Sample pH was determined immediately after collection with an Activon 105 portable pH meter.

The expected flux rates of ammonium ions from the enriched dome water into the underlying sediment were calculated with the Stokes-Einstein equation for diffusion (Crank *et al.*, 1981):

$$C = M/2.(\pi Dt)^{-1/2}.\exp(-r^2/4Dt) \qquad (Equation\ 2)$$

where C = concentration of solute,
M = quantity of solute emitted at $t=O$ from unit area of the plane of origin,
D = the diffusion coefficient,
t = time,
r = the distance of the point of measurement from the plane of source.

This equation describes the decrease of a solute with time due to simple diffusion. By considering the underlying sediment as an infinite sink the equation would give the maximum rate of diffusion possible and enable us to speculate on the possibility of active uptake by sediment or water column organisms.

Results

Pore-Water Ammonium, Nitrate/Nitrite, and Sediment-Water Column Fluxes

Both sediment types showed the same concentration of free ammonium at 15cm depth (38μg atoms NH_4^+-N.l^{-1}) but above this depth the concentration gradients were considerably different (Fig. 3). In the very fine sand site the concentration had a pronounced peak at 5cm depth (50μg atoms NH_4^+-N.l^{-1}) with the lowest concentration in the top 1cm of sediment (18μg atoms NH_4t-N.1^{-1}). By comparison the coarse sand site showed a peak ammonium concentration at 15cm depth (38μg atoms NH_4^+-N.l^{-1}), with a gradual decrease toward the top 1cm of sediment (8μg atoms NH_4^+-N.l^{-1}), (Fig. 3). Nitrate/nitrite concentration gradients for both sediment types showed a small peak just below the sediment surface; 6.75 $\pm$ 8.8μg atoms NO_3^-/NO_2^--N.l^{-1} (n=4) at 5cm in the coarse sand and 7.0 $\pm$ 7.8μg atoms NO_3^-/NO_2^--N.l^{-1} (n=4) at 2.5cm in the very fine sand (Fig. 4). In both sediment types, NO_3^-/NO_2^- concentrations decreased with increasing sediment depth and concentrations were usually barely above detection limits.

Despite the existence of reasonably strong concentration gradients of NH_4^+ and the occurrence of measurable amounts of NO_3^-/NO_2^- in the sediments at One Tree Is., no flux of dissolved NH_4^+ or NO_3^-/NO_2^- into the overlying water column was observed from either type of sediment studied. Also no dissolved ammonium was detected in the surrounding seawater at the site with coarse sand, but water at the site with very fine sand consistently had an NH_4^+ concentration of 1.9 $\pm$ 0.1μmols.l^{-1}. NO_3^-/NO_2^- ions were undetectable in the surrounding water over both study sites.

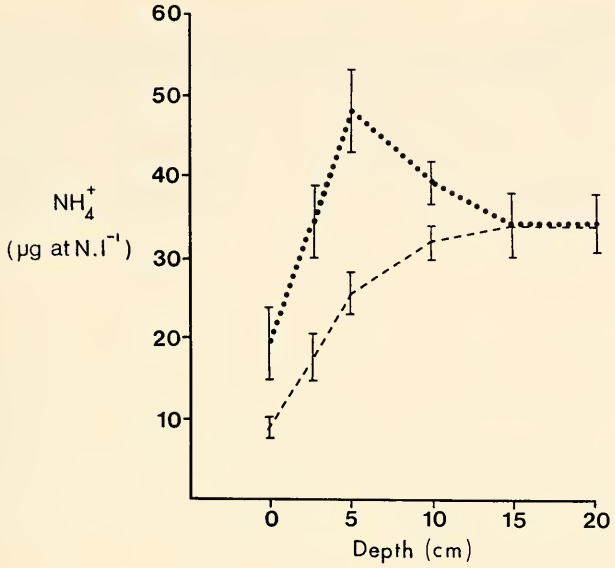

Fig. 3. Concentration gradients of ammonium in pore-water of two sediment types at One Tree Is. Vertical bars are 95% confidence limits (n = 4).
●●●●●● Very fine sand; – – – – – Coarse sand.

Using the concentration gradients from the top 5cm of each sediment type the expected rates of NH_4^+ efflux from the sediment surface were calculated with the Stokes-Einstein equation. This was corrected for temperature variation and used a diffusion coefficient of 19.8 × $10^{-6}cm^2.s^{-1}$ (Li and Gregory, 1974). The resulting flux rates were 2.55μg atoms $N.m^{-2}.h^{-1}$ for coarse sand, and 1.85μg atoms $N.m^{-2}.h^{-1}$ for the very fine sand.

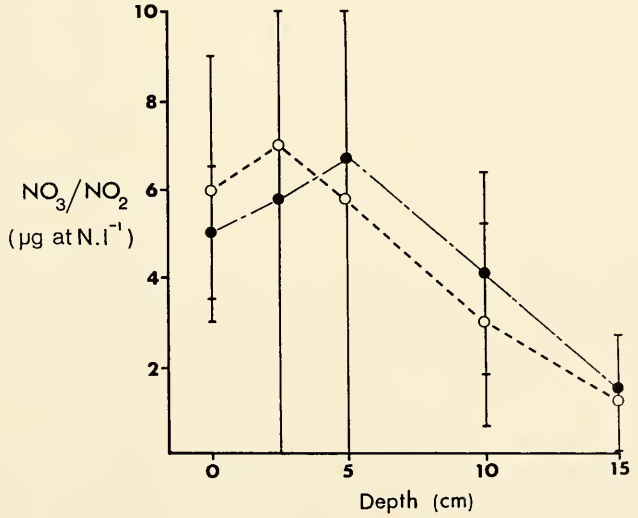

Fig. 4. Concentration gradients of nitrate/nitrite in pore-water of two sediment types at One Tree Is. Vertical bars are 95% confidence limits (n = 4).
○– – – – ○ Very fine sand; •—— – —— • Coarse sand.

Enrichment Experiments

Experiments in sites with both the very fine sand and coarse sand showed approximately exponential loss of NH_4^+ over the experimental period (Fig. 5**A**,**B**). Above the very fine sand the rate of loss showed a short but distinct plateau centred on the time of total dark, approximately 7.5 hours after the start of the experiment. The plateau lasted approximately 4 hours and was followed by a slower rate of decrease in NH_4^+ ions than previously observed. Above the coarse sand there was no plateau, and the decrease in ammonium ion concentration over time was approximately exponential (Fig. 5**B**).

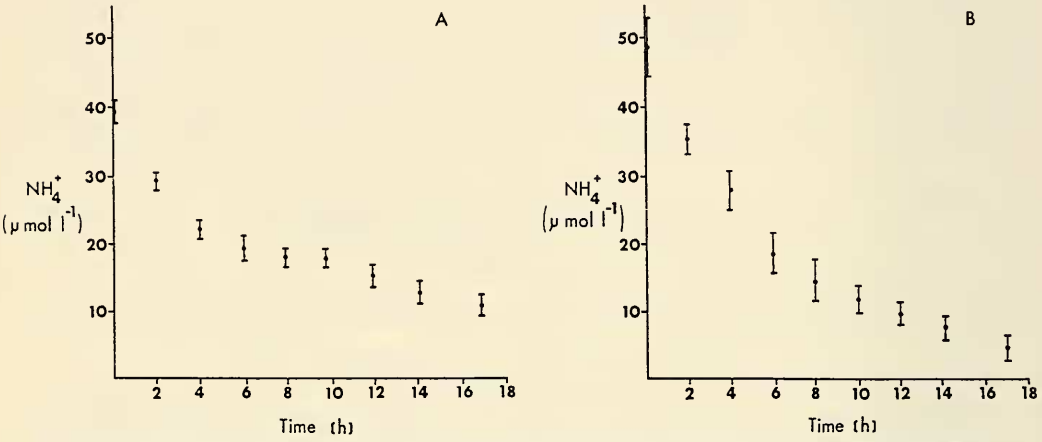

Fig. 5. Concentrations of ammonium in enriched dome water over very fine sand (**A**), and coarse sand (**B**) at One Tree Is. Note the plateau between 6 and 10 hours at the very fine sand site. Total dark occurred at 7 hours for both experiments. Vertical bars are 95% confidence limits (n = 4).

Using the Stokes-Einstein equation for diffusion, the calculated concentrations of ammonium ions in the water under the domes after 17 hours would be 10μM NH_4^+ and 12μM NH_4^+ for very fine and coarse sands respectively (this assumes diffusion at the sediment surface into an infinite sink for NH_4^+). The concentrations observed after 17 hours were 10 $\pm$ 2μM for very fine sand and 5 $\pm$ 2.5μM for coarse sand. These values are equal to or less than those calculated, indicating that the ammonium ions were being taken up at near maximal rates.

At the end of the experimental period, there was no significant difference between individual domes in the two types of sediments, or between treatments, for mean values of pH, temperature or dissolved oxygen in the water enclosed by the domes, and there was no difference between entrapped dome water and unenclosed water for these parameters (Table 1). Also, there was no decrease in the concentration of ammonium ions in the control bottles of enriched water incubated over the 17 hour period indicating that there was no detectable uptake of ammonium ions by water column organisms.

Discussion

Physical variations, such as grain size, have received little attention in relation to nutrient levels in sediments of coral reefs (e.g. Entsch *et al.*, 1983). We have shown here (Fig. 3) that the ammonium concentration in the first 15cm of sediment is higher in the fine compared to the coarse sediment. Although many factors may be involved in determining these gradients, it is likely that differences in the metabolic activity of microbial populations of each sediment type varies the nutrient levels. This conclusion is

TABLE 1

Mean values and standard deviations of dissolved oxygen, pH, and temperature in enriched dome water, control dome water, and surrounding seawater over the two study sites for enrichment experiments January, 1985

		O_2 (ppm)	pH	Temperature (°C)
Very Fine Sand.	Enriched	5.93 ± 1.21	8.03 ± 0.09	28.25 ± 0.82
	Control	5.82 ± 1.23	8.06 ± 0.10	28.25 ±0.86
	Seawater	6.17 ± 0.73	8.08 ± 0.18	28.57 ± 0.90
Coarse Sand.	Enriched	7.37 ± 1.67	8.01 ± 0.18	27.88 ± 1.16
	Control	6.87 ± 2.00	7.99 ± 0.18	27.95 ± 1.24
	Seawater	6.20 ± 1.51	7.96 ± 0.14	28.00 ± 1.45

consistent with work elsewhere that shows grain size and porosity influence the nutrient levels of sediments, and are correlated with changes in sediment microbial and invertebrate populations (Dale, 1974; Jansson, 1967).

The concentration gradients from NO_3^-/NO_2^- observed here are similar to those found in coral reef sediments elsewhere (Corredor and Morell, 1985) and the concentrations found at One Tree Is. fall in the same range as found in sediments on the northern Great Barrier Reef (Boon, 1986). We suggest that the peak in NO_3^-/NO_2^- concentrations close to the sediment surface is due to bacterial nitrification which has been shown in other types of marine sediment to occur in the oxygenated zone (e.g. Henriksen, 1980; Henriksen *et al.*, 1981). Ammonium needed for this process would be supplied from the deeper anoxic zones where ammonification occurs and the concentration gradients observed here are more than adequate for this process. The absence of a NO_3^-/NO_2^- flux from the sediments into the water column is consistent with work on fluxes by Harrison (1983), who found that they were mostly negative (i.e. from the water column into the sediment). It is likely that the NO_3^-/NO_2^- pool, which is small compared with the ammonium pool is either utilized as a nitrogen source, or used in denitrification by the microbial population in the top layers of sediment.

For dissolved ammonium, concentration gradients and pools were up to an order of magnitude higher than for NO_3^-/NO_2^-. Despite the relatively steep concentration gradients of dissolved ammonium ions, and although an efflux of NH_4^+ ions has been observed elsewhere for coral reef sediments (Williams *et al.*, 1985), no efflux of ammonium ions from the sediment into the water column was observed in this study. Using the NH_4^+ concentration gradients in the One Tree reef sediments, and assuming a passive system, there should be a theoretical flux of NH_4^+ ions out of the sediment of 2.55μmols NH_4^+-N.m^{-2}.h^{-1}, for coarse sand; and 1.85μmols NH_4^+-N.m^{-1}.h^{-1}, for very fine sand.

The fact that no such flux was observed indicates that an active uptake process must be occurring in the top layers of sediment and this is substantiated by the fact that when the water under the domes was enriched with ammonium ions, its concentration decreased over time despite an opposing concentration gradient in the underlying sediments. Applying the Stokes-Einstein equation for diffusion (Crank *et al.*, 1981) of ammonium ions out of the domes and into the sediment, it is possible to show that ammonium was leaving the dome at near maximum rates (assuming a diffusive process). Ammonium ions are not used by organisms in the water column as shown by the bottle experiments, thus it is concluded that the ammonium is rapidly taken up and used, or modified, by organisms in or on the top layers of sediment; despite the fact that these organisms are also receiving a flux of ammonium ions from deeper sediments.

Use of free ammonium ions by marine microalgae is well known (e.g. Syrett, 1953; Goldman and Glibert, 1982) and microscopic inspection of water from the enriched domes and the top 1cm of sediment showed a suite of microalgae to be present in the sediment, but only rarely present in water samples. Thus microalgae may at least in part be responsible for the uptake of ammonium from the sediment but as indicated above other processes such as nitrification and denitrification may also change ammonium concentrations. Because of the size of the ammonium pool in One Tree reef sediments, however, it is unlikely that it could all be processed via nitrification and subsequent denitrification. If this were the case, then the corresponding denitrification rate would be approximately 2.4μmols $N_2O.m^{-2}.h^{-1}$. This is almost ten times the rate observed by Seitzinger and D'Elia (1985) for coral reef sediments (0.3μmols $N_2O.m^{-2}.h^{-1}$), and comparable to rates found in marine sediments with a much higher organic input (Nishio *et al.*, 1983). The level of nitrification and denitrification in One Tree reef sediments is presently being studied.

Apart from microbial composition, other biological factors likely to affect sediment nutrient levels are bioturbation and grazing which occur in surface layers. Both types of sediment discussed here are disturbed by burrowing shrimps and deposit feeding organisms such as holothuria. Such organisms significantly affect bacteria in sediments (Juniper, 1981). At One Tree reef, most turbating organisms were observed in the top 15cm of sediment where the concentration gradients between the two sediment types are most different.

In addition, the coarse sand is often exposed to currents which can totally rework the top 5 to 10cm of sediment (Frith, 1985). Although such currents were not observed during the period of this study, they occur fairly frequently. Combined with the activities of turbating organisms such currents probably affect the incorporation of organic matter into, and general stability of the sediment.

In summary these results show that the sediments at One Tree reef do not release free dissolved ammonium, nitrate or nitrite ions for use by primary producers or other organisms in the water column or hard substrate communities, but appear to contain microorganisms capable of using and modifying this nitrogen. Presumably nitrogen ultimately leaves the sediments in forms other than dissolved ions possibly via grazers of micro-organisms, but the processes involved are still to be identified.

Acknowledgements

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